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Report

The Alarming Decline of Mediterranean Fish Stocks

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Summary

In recent years, fisheries management has succeeded in stabilizing and even improving the state of many global fisheries resources [1–5]. This is particularly evident in areas where stocks are exploited in compliance with scientific advice and strong institutional structures are in place [1, 5]. In Europe, the well-managed northeast (NE) Atlantic fish stocks have been recovering in response to decreasing fishing pressure over the past decade [3–6], albeit with a long way to go for a universal stock rebuild [3, 7]. Meanwhile, little is known about the temporal development of the European Mediterranean stocks, whose management relies on input controls that are often poorly enforced. Here, we perform a meta-analysis of 42 European Mediterranean stocks of nine species in 1990–2010, showing that exploitation rate has been steadily increasing, selectivity (proportional exploitation of juveniles) has been deteriorating, and stocks have been shrinking. We implement species-specific simulation models to quantify changes in exploitation rate and selectivity that would maximize long-term yields and halt stock depletion. We show that stocks would be more resilient to fishing and produce higher long-term yields if harvested a few years after maturation because current selectivity is far from optimal, especially for demersal stocks. The European Common Fisheries Policy that has assisted in improving the state of NE Atlantic fish stocks in the past 10 years has failed to deliver similar results for Mediterranean stocks managed under the same policy. Limiting juvenile exploitation, advancing management plans, and strengthening compliance, control, and enforcement could promote fisheries sustainability in the Mediterranean.

Results

The statuses of fish stocks in the Mediterranean and Black Seas exploited by European Union (EU) countries (hereafter referred to as Mediterranean stocks) are analytically assessed by the General Fisheries Council for the Mediterranean (GFCM) of the Food and Agriculture Organization (FAO) and by the Scientific, Technical and Economic Committee for Fisheries (STECF) of the EU. Stock assessments are produced over 30 management areas (geographical subareas [GSAs]) established by the GFCM (Figure 1). The number of analytically assessed stocks has increased significantly over the past 10 years [8]. GFCM and STECF also provide scientific advice on the basis of the observed levels of exploitation rate, quantified as the fishing mortality (F; Table S1 available online). This advice is in accordance with the EU's Common Fisheries Policy (CFP), which dictates that fish stocks should be exploited at a level that generates the maximum sustainable yield (MSY) [9]. Therefore, the desired exploitation state for each stock is for F to be at or below the level producing the MSY (F_{MSY}). The development of stock size, quantified as the spawning stock biomass (SSB), is also reported in Mediterranean stock assessments. However, no relevant limit reference points (Table S1) are available for most stocks [10]. Fisheries selectivity (Table S1) associated with high juvenile exploitation is a characteristic feature of Mediterranean fisheries [8, 11].

Fisheries management of Mediterranean stocks relies on input controls to achieve the goals of the CFP, i.e., fishing effort regulations (e.g., spatiotemporal fishing restrictions) and technical measures (e.g., minimum landing sizes) [8, 11]. Notably, input controls in the Mediterranean are often inconsistent with scientific evidence. For example, many minimum landing sizes are not biologically sensible [8], and sensitive habitats, such as nurseries and biodiversity hotspots, are exposed to high fishing pressure [12]. Also, there is absence of output controls (catch limits) and lack of strong institutional structures, which relates to inadequate levels of compliance [8] (Table S1).

Here, we investigate the aggregate (cross-stock) temporal trends of 42 Mediterranean stocks in 1990–2010 to reveal a steady deterioration of the exploitation regimes (exploitation rate and selectivity) and SSB (Figure 2). The stocks that were examined included 12 hake (*Merluccius merluccius*), 12 red mullet (*Mullus barbatus*), seven anchovy (*Engraulis encrasicolus*), six sardine (*Sardina pilchardus*), and five other demersal stocks (striped red mullet, *Mullus surmuletus*; black anglerfish, *Lophius budegassa*; common pandora, *Pagellus erythrinus*; sole, *Solea solea*; turbot, *Psetta maxima*) (Table S2). The examined stocks produced about half of the total landings of bony fishes (excluding tunas and billfishes) caught by European Mediterranean and Black Sea countries in 2010 [13]. Hake and anchovy produced the highest revenues of all marine species caught in the Mediterranean and Black Seas in 2010 [14]. We also investigated spatial differences in the temporal development of the exploitation regimes and SSB over a longitudinal gradient by analyzing aggregate trends within three different marine regions (west, central, and east) (Figures 1 and S1).

Exploitation rate of each stock was expressed by F/F_{MSY}, where $F/F_{MSY} > 1$ indicates stocks exploited unsustainably [7]. F_{MSY} values for the 29 demersal stocks (hake, red mullet, and other demersal stocks) were extracted from their assessment reports, whereas for the 13 small pelagic stocks (anchovy and sardine), F_{MSY} values were inferred from the exploitation rate reference points reported in their assessment reports (Table S2). Aggregate exploitation rate increased steadily over the studied time period (Figure 2A). After 1996, aggregate exploitation rate was increasing on average by 0.08 units per year, and stocks were exploited on average 3–5 times above their F_{MSY}. In 2010, for the first time, all stocks examined were exploited above F_{MSY}. Hake stocks

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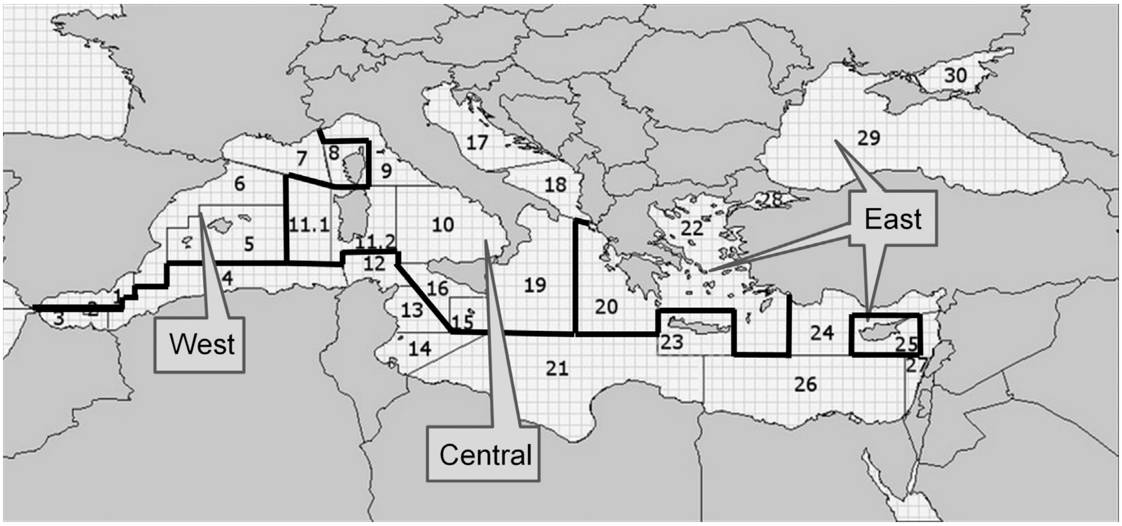

Figure 1. Geographical Subareas of the Mediterranean and Black Seas

Thin black lines indicate the borders of the 30 Mediterranean and Black Sea GSAs established by the GFCM. Bold black lines indicate the division into west, central, and east areas, which was performed for this study. The map illustrating the GFCM GSAs was retrieved from http://www.gfcm.org/gfcm/en.

experienced the highest exploitation rates, being exploited on average 7.4–11.6 times above F_{MSY} after 1996. The highest levels of F (12–19.2 times above F_{MSY}) were observed in the hake stock of GSA 6. From all species groups examined, sardine stocks were the ones exploited at rates closer to F_{MSY} (F/F_{MSY} < 1.7 after 2001). Aggregate exploitation rates were higher in the west and central areas compared to the east area from 2005 onward (Figure S1A).

Fisheries selectivity at the population level [15] was expressed as relA50, i.e., the difference in years (y) between the age at which 50% of the fish are selected if they encounter the fishing gears (A_{s50}) and the age at which 50% of the fish are mature (A_{m50}). Negative values of relA50 indicate that fish that encounter the gears tend to get caught before they have the chance to spawn at least once. Aggregate relA50 decreased continuously in 1990–2006 at an average rate of 0.1 y per year and stabilized in negative values from 2006 onward (Figure 2B). Overexploitation of juveniles was particularly evident in the case of hake stocks, with fish being selected on average 0.6–1.9 years before they matured. Selectivity in small pelagic stocks (sardine and anchovy) was more sustainable, with fish being selected on average more than 0.4 years after they matured. Similar to exploitation rate, selectivity in the west and central areas was associated with higher juvenile exploitation compared to the east area after 2005 (Figure S1B).

SSB of each stock was standardized by dividing with the dynamic unexploited stock size (SSB_0), which is the expected equilibrium SSB if F is set to zero [16]. In the absence of biomass reference points for 37 of the 42 studied stocks, this standardization allowed the development of SSB to become comparable across stocks and species. Aggregate standardized biomass decreased steadily over the studied time period, with the average rate of decrease being 0.01 units per year after 1996 (Figure 2C). This rate of decrease corresponds to stocks losing on average 1% of their SSB_0 per year. SSB of hake stocks remained on average at a striking 1%–3% of their SSB_0 after 1997. Small pelagic stocks were in better shape, with their SSB remaining on average above 25% of their SSB_0 over the studied time period. Aggregate standardized biomass was lower in the west compared to the central and east up until 2008, but it was similarly low in all three areas in 2009 and 2010 (Figure S1C). Further details on the construction of the time series and the analysis of temporal trends can be found in the Supplemental Experimental Procedures.

To identify combinations of exploitation rate and selectivity that would maximize long-term SSB and yield (Y) of the main commercial Mediterranean species, we used four age-structured population models parameterized for hake, red mullet, sardine, and anchovy. In this case, exploitation rate was quantified as the F of the fully selected age class rather than as the F/F_{MSY}, due to the dependence of F_{MSY} on selectivity [17]. Each model run commenced with the population at a virgin state, and a random set of F, A_{s50}, and A_{m50} values was applied. Next, population numbers at age were projected forward for 100 years, and the 100th year's SSB and Y were extracted [18]. Annual recruitment (Table S1) within each model run was inferred from the stock size of the previous year using a random stock-recruitment relationship. To illustrate the combined effects of F and relA50 on both SSB and Y, we created two contour plots for each species, where values of SSB and Y were linearly interpolated onto 40 × 40 grids (Figures 3 and 4). Further details on the operating models, forward projections, and contour plot construction can be found in the Supplemental Experimental Procedures.

The biomass contour plots suggested that if fish were selected by gears a few years after maturation, stocks could sustain a great range of exploitation rates (Figure 3). For hake, highest long-term Y at sustainable levels of stock depletion (SSB/SSB_{virgin} > 30%; [19]) would be extracted if fish were selected at least 3.5 years after they matured (Figures 3A and 4A). Similarly, optimal harvesting for red mullet would be 2+ years after fish matured (Figures 3B and 4B), for sardine 1.3–2.5 years after fish matured (Figures 3C and 4C), and for anchovy 0.8–1.1 years after fish matured (Figures 3D and 4D).

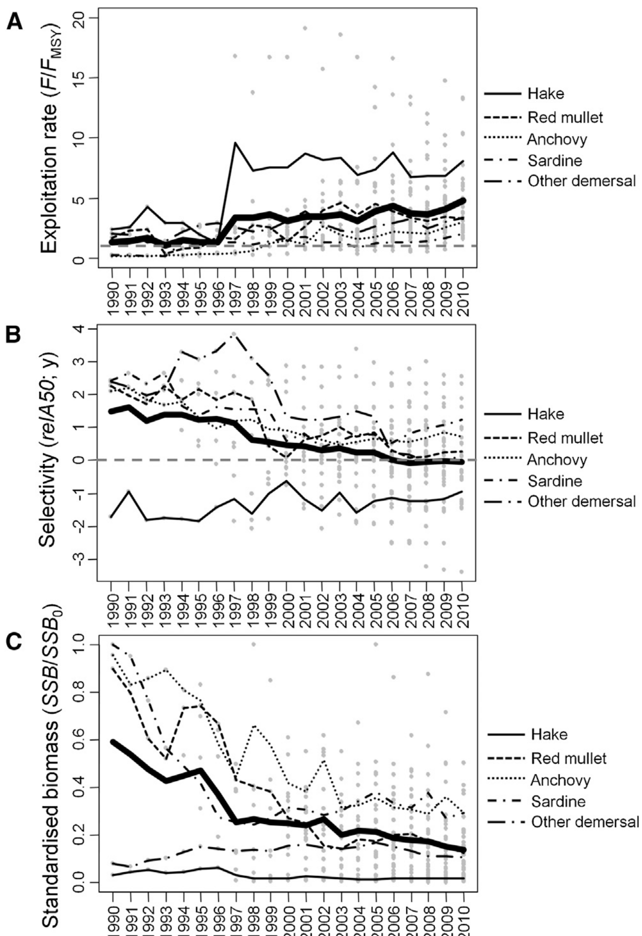

Figure 2. Temporal Development of the Exploitation Rate, Selectivity, and Biomass of Mediterranean Fish Stocks

(A–C) The temporal development of relative exploitation rate (A), selectivity (B), and standardized spawning stock biomass (C) of European Mediterranean and Black Sea fish stocks. Grey dots indicate annual observations for each stock. Bold black lines indicate the average values over all stocks by year. Gray dashed line on (A) indicates the exploitation rate limit ($F/F_{MSY} = 1$), and gray dashed line on (B) indicates the relA50 = 0 y value, corresponding to A_{s50} being equal to A_{m50}. See also Table S1 and Figure S1.

Under optimal selectivity, stocks would produce high sustainable yields, even for high levels of fishing mortality.

When the optimal combinations of F and relA50 identified by the simulation analysis were compared to the latest empirical values observed in 40 actual stocks, a distinct mismatch emerged, which was particularly evident in the case of the demersal species. All 12 hake stocks and 6 out of 14 red mullet stocks lay within the lowest SSB area ($SSB/SSB_{virgin} < 5\%$) due to the combination of high F and low relA50 values (Figures 3A and 3B). No red mullet or hake stocks lay within safe biological limits. The effects of unsustainable selectivity were particularly evident in the case of hake stocks, in which fish are currently selected 0–3 years before they mature compared to ~3.5 years after they mature, which would be needed for stocks to sustain the applied high Fs (Figure 3A). For the current hake selectivity to be sustainable, 10- to 20-fold reductions in F would be required. In red mullet stocks, in which fish are currently selected around the age that they mature, a sustainable long-term SSB would be achievable under current F if fish were selected 1–2.5 years later (Figure 3B). In small pelagic stocks, three out of six sardine stocks (Figure 3C) and five out of eight anchovy stocks (Figure 3D) are currently exploited in a way that secures long-term sustainable SSB. For the six small pelagic stocks currently lying outside safe biological boundaries, sustainability could be secured through small improvements in selectivity so that fish could be caught when they are 0.1–0.8 years older (Figures 3C and 3D). Notably, out of all 40 empirical stocks examined, only two anchovy stocks lay in the area of the highest Y (Figure 4), indicating that most Mediterranean fisheries extract much lower yields than those that stocks could support. When different areas were compared, current exploitation regimes were slightly better in the west for hake stocks and in the west and east for red mullet stocks (Figures 3 and 4). No particular differences between the different areas were observed in the case of anchovy and sardine stocks.

Discussion

This meta-analysis of the temporal development of 42 Mediterranean fish stocks covered a 21-year period (1990–2010) to reveal that the poor current state of most stocks, which has also been identified by other recent studies [8, 10], is just a snapshot of a steadily deteriorating trend. In addition to Mediterranean stocks dwindling in the past 21 years, exploitation rate and fisheries reliance on juveniles have both been continuously increasing, leaving no room for optimism for the stocks' prospects. The shrinking of Mediterranean stocks that is revealed here explains the declines that have been observed in Mediterranean landings, especially of demersal fish species, over the past two decades [20].

The deteriorating trends of Mediterranean fisheries are likely to continue if no action is taken. The simulation analysis suggests that such action should focus not only on reducing exploitation rate but mainly on improving selectivity. Previous studies in the Mediterranean and elsewhere have suggested that if fish are caught at a size at which a cohort attains its highest biomass (L_{opt}), growth overfishing is restrained, and long-term Y and SSB can increase substantially [8, 21]. Furthermore, catching fish after they have spawned at least once also hinders recruitment overfishing [22, 23]. The selectivity metric used here (the difference between A_{s50} and A_{m50}) captures the effect of both growth and recruitment overfishing because the age corresponding to L_{opt} is usually higher than A_{m50} [8, 21], and it confirms the expected benefits from protecting small fish. Our findings also reveal, in line with previous studies [8], that selectivity improvements in the Mediterranean have a greater potential to benefit the state of stocks of long-lived demersal species than the state of stocks of short-lived small pelagic species.

The examination of the combined effects of a wide range of F and selectivity values on long-term Y and SSB broadens the findings of [8] to suggest that an optimal exploitation regime is more than a single value of F applied at an optimal selectivity level. Rather, there is a species-specific continuum of optimal combinations of F and selectivity corresponding to areas of high long-term Y and SSB. Implementing a similar simulation approach on a stock-by-stock basis could serve management by assisting in the creation of road maps that illustrate changes in F and selectivity required for stocks to move toward more sustainable and/or profitable states. This approach is very topical in the context of the new CFP, which supports

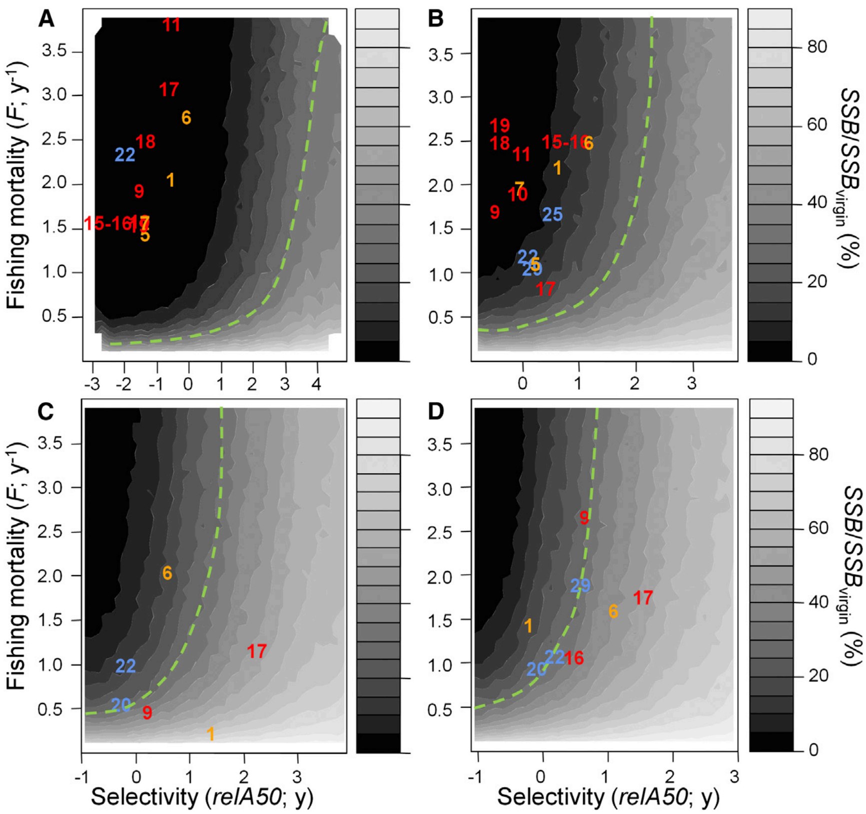

Figure 3. Effect of Different Combinations of Exploitation Rate and Selectivity on the Long-Term SSB of Simulated Hake, Red Mullet, Sardine, and Anchovy Stocks

(A–D) Grayscale contour plots indicate the percentage of virgin SSB remaining after 100 years of exploitation of simulated stocks of hake (A), red mullet (B), sardine (C), and anchovy (D) in response to F and relA50 (see Supplemental Experimental Procedures). Green dashed lines indicate the position of the 30% contour, which corresponds to the value considered as a safe biological limit in data-limited stocks [19]. Numbers indicate relA50 and F combinations of empirical stocks (average values of the last three available years) and refer to the GSA where each stock is found (Figure 1; Table S2). Orange indicates west stocks. Red indicates central stocks. Blue indicates east stocks.

the transition toward results-based management regimes in which the industry will have greater flexibility in defining the strategies that will be adopted to achieve sustainability [24].

Meta-analysis of stock assessment data makes general trends and patterns clearer and helps to synthesize the results of individual stock assessments into good management strategies [25]. However, as it has also been noted in previous similar meta-analyses [6, 22, 25], the results of this study should be interpreted with caution, given that they are based on outputs of stock assessment models that involve various levels of uncertainty. Nevertheless, the data analyzed in this study are the best available for Mediterranean stocks and are therefore the data used by the EU to produce official management advice through STECF.

This study reveals a two-speed performance in European fisheries management and suggests that succeeding management in the northeast (NE) Atlantic may have led the EU to overlook the "skeleton in the closet," i.e., Mediterranean fisheries. This discrepancy needs to be acknowledged because the biological, financial, and social consequences of widespread stock collapses in the Mediterranean would be immense. The reversal of fish stock decline in the NE Atlantic over the past 10 years was a result of implementing multiannual management plans (Table S1), featuring both catch limits and effort controls in a context of strong institutional structures and high levels of compliance [3–5]. Multiannual management plans with specific long-term general objectives (e.g., high yields, sustainable stock biomass, etc.) and a clear strategy to realize these objectives [5, 26] could benefit Mediterranean fisheries as well. The strategy implemented in such management plans should ideally include both input controls and catch limits as agreed decision rules, ensure protection of juveniles, and take into consideration the societal and economic effects of the management transition. There is an obvious socioeconomic cost related to any type of management transition, and, with multiple fleet segments existing in the Mediterranean, allocating this cost evenly to different stakeholders may be challenging. One way to assess the impact of exploitation rate reductions and changes in selectivity would be to consider the social benefit related to the fishery as a whole, as opposed to the private benefit to the fishing fleets [27]. In any case, examining the socioeconomic viability of management transitions in the Mediterranean (e.g., via explicit cost-benefit analysis) is of critical importance given the large small-scale fisheries sector, the artisanal nature of fisheries (Table S1), and the high dependence of several coastal communities on fishing-related activities [8, 11]. Note that the great number of small boats operating along the extensive European Mediterranean coastline would demand a large investment of resources in order to effectively enforce input controls. Moreover, there are several landing sites in the Mediterranean, and landings do not always pass through official quays. Therefore, the adoption of catch limits would be ineffective without a more stringent monitoring of landings and catches. Appropriate multiannual plans, accompanied by higher levels of compliance, effective control and enforcement, and establishment of some rights-based incentives to the fishing communities [28], could change the declining course of Mediterranean fisheries. The ongoing CFP reform [29] provides a unique opportunity to develop advanced management regimes that will be more successful in safeguarding Mediterranean fisheries resources than current management regimes.

This study suggests that the CFP has not succeeded in improving the state of European Mediterranean commercial fish stocks over the past two decades, in contrast to the European NE Atlantic stocks. The increasing trend of exploitation rate observed here is particularly alarming because it is probably affecting many more stocks and species than the ones examined in this meta-analysis, due to the multispecies nature of Mediterranean fisheries [11]. There are other data-limited marine areas in the developing world, such as the Chinese seas [30], the Sub-Saharan African seas [31], and many tropical estuaries [32], that exhibit similar characteristics to the

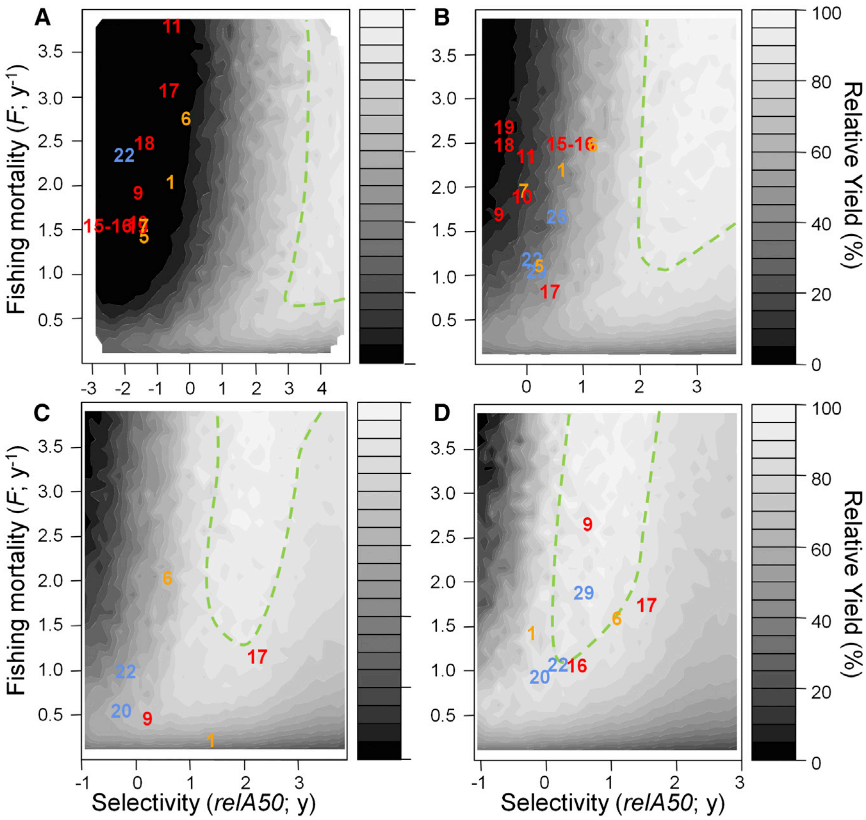

Figure 4. Effect of Different Combinations of Exploitation Rate and Selectivity on the Long-Term Yield of Simulated Hake, Red Mullet, Sardine, and Anchovy Stocks

(A–D) Grayscale contour plots indicate the relative yield extracted on the 100th year after the beginning of exploitation from simulated stocks of hake (A), red mullet (B), sardine (C), and anchovy (D) in response to F and relA50 (see Supplemental Experimental Procedures). Relative yield has been obtained by dividing Y by its maximum value [17]. Green dashed lines indicate the position of the 90% contour, marking the border of the area where the highest decile of relative yields is produced. Numbers indicate relA50 and F combinations of empirical stocks (average values of the last three available years) and refer to the GSA where each stock is found (Figure 1; Table S2). Orange indicates west stocks. Red indicates central stocks. Blue indicates east stocks.

Mediterranean (i.e., management reliant on input controls, low levels of compliance, and poor enforcement). Current findings may apply to these cases as well; therefore, fish stock decline reversals in the developed world should leave no room for complacency.

Supplemental Information

Supplemental Information includes Supplemental Experimental Procedures, one figure, and two tables and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2014.05.070.

Author Contributions

P.V. and C.D.M. designed the study. P.V. performed the analysis. P.V., C.D.M., and G.T. wrote the manuscript.

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